Integrated Refrigeration and Storage of Cryofuels

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Low molecular weight and high specific impulse makes liquid hydrogen (LH_2) a superior propellant for rocket applications; but its low normal boiling point (NBP) and density make utilization difficult and costly compared to other cryofuels. The US Atomic Energy Commission, and subsequently NASA and the US Air Force, pioneered the development of large scale LH_2 systems in the 1950s, but over time the technology in the industrial gas industry has seen tremendous gains. The space industry uses its cryogens in a different manner than most industries, storing up large quantities for periodic batch use rather than continuous feed, and requiring the product to be supplied to the end process in liquid form, as opposed to liquid storage but gaseous supply. NASA's space launch cryogenic ground systems and processes are still based on proven but inefficient technologies from the 1960s. As a result, over the duration of the Space Shuttle program approximately 50% of the hydrogen purchased was lost, vented to the atmosphere due to system heat leak and cooldown of hardware [1].

A technology to help maximize efficiency of spaceport cryogenic processes is Integrated Refrigeration and Storage (IRAS), or integrating modern cryogenic refrigeration units with liquid storage vessels. Brayton cycle helium refrigerators are available in a range of capacities and temperatures with demonstrated high efficiency and low maintenance operations. A suitable refrigerator is used to supply a direct flow of gaseous helium refrigerant to the cold heat exchanger (HX) integrated within the tank, and distributed within the bulk volume of liquid. Distribution of the cold power is the key to obtaining an effective overall heat lift without the large conduction heat leak penalty associated with a "point-cold" cryocooler arrangement. The IRAS technology is an approach that directly couples the cold HX with the cryogenic liquid so as to minimize thermal resistances and expedite heat transfer, allowing the bulk fluid properties to be controlled. Rather than being limited to managing the cryofuel storage states only by mass addition and removal (pressurization and venting), an IRAS system offers full control of the state of the fluid using addition and removal of thermal energy. Such control allows for greater operational efficiency, greater control of ground operations, and enhanced performance benefits.

The IRAS technology has been developed at the Kennedy Space Center to demonstrate several novel cryogenic operations including:

- Zero Loss Storage and Transfer – Remove system heat loads during both steady-state heat leak and transient cooldown operations
- Propellant Densification – Control the storage state of LH_2 below the NBP
- In-Situ Liquefaction – Provide liquefaction of gaseous hydrogen (GH_2) inside the storage tank
- Zero Loss Cooldown – Provide cooldown of storage tanks with no product loss

The ability to control the energy in a tank is a new operational capability, and enables users to examine cryogenic storage systems from a different perspective. Consider a map that shows the net rate of heat flow crossing the system boundary on the X-axis—normal heat leak plus the vaporizer heating minus the refrigeration power; and the net rate of mass crossing the boundary on the Y-axis—mass flow rate of pressurant gas minus the rate of venting. The net heat flow can be non-dimensionalized by dividing by the normal heat leak, and is hereby defined as the refrigeration ratio (eqn. 1); while the net mass flow can

be non-dimensionalized by dividing by the normal evaporation rate (NER) and is defined as the mass ratio (eqn. 2).

$$\mathrm{RR} = \frac{\dot{Q}_{HL} + \dot{Q}_{Vap} - \dot{Q}_{Ref}}{\dot{Q}_{HL}} \qquad \{\text{eqn. 1}\}$$

$$\mathrm{MR} = \frac{\dot{m}_{Press} - \dot{m}_{Vent}}{\dot{m}_{NER}} \qquad \{\text{eqn. 2}\}$$

In Figure 1, the positive X coordinate shows when the tank is receiving net heat from the environment: the negative X coordinate shows when the tank is dumping heat to the environment, and the Y-axis is the adiabatic line. Similarly, negative Y values signify net mass flow out of the tank, positive Y values signify mass flow into the tank, and along the X-axis the system is closed. At the origin, the system is closed and adiabatic, and the pressure will remain constant. An isobar can be drawn thru the origin at some non-constant negative slope. All operations above that isobar cause an increase in tank pressure and operations below the line result in a pressure decrease.

Without IRAS technology cryogenic operations are extremely limited in capability. Daily operations typically consist of venting at the NER (point A on the isobar) in order to accommodate heat leaking into the tank. If the vent valve is closed, vent flow drops to zero and heat leak causes self-pressurization, shown as point B. Prior to liquid transfer the tank is pressurized by the vaporizer, adding heat and moving the operation to point C. Sometimes liquid tanks are pressurized by gas trailers, as indicated by point D. Finally, when the tank is vented the operation would lie somewhere along the line between E-A, depending on the vent flow rate, and will eventually settle back at point A for daily operations. Without IRAS, all operations will occur on or to the right of the line EABD, the “passive line.”

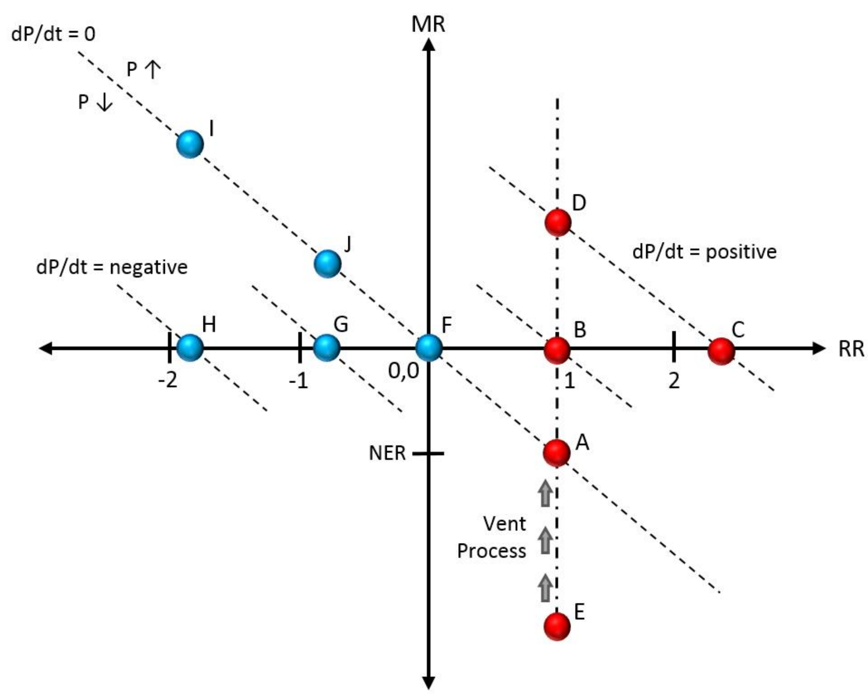

Figure 1. Dimensionless mass and energy chart showing the control capabilities gained with IRAS (blue dots)

IRAS opens up the wide range of cryogenic storage and transfer operations located to the left of the passive line—most notably, the origin (point F), where the system is adiabatic, closed, and isobaric, and is defined as zero boil-off (ZBO). When the refrigeration ratio increases beyond ZBO the tank pressure will decrease and liquid will densify (points G and H). Steady liquefaction occurs along the isobar when the mass flow into the tank is provided (points I and J).

The GODU-LH2 project, recently completed at NASA Kennedy Space Center, demonstrated operations located at all points of Figure 1—red points represent legacy operations while blue points represent new capabilities proven by the GODU-LH2 project using IRAS—showing that full control of the state of the fluid is possible as well as practical [2,3]. A 125,000 liter LH_2 tank, depicted in Figure 2, was retro-fitted with a novel internal HX and coupled to an 860 W Brayton helium refrigerator for this work [4,5]. Testing also included simplified large-scale production of slush hydrogen below 14 K. The technology of IRAS is extensible to other cryofuels including liquid methane (or LNG) and liquid oxygen as well. In addition, other fluid control issues related to boil-off, such as aging of LNG or enrichment of liquid air, could be addressed with a suitable IRAS approach.

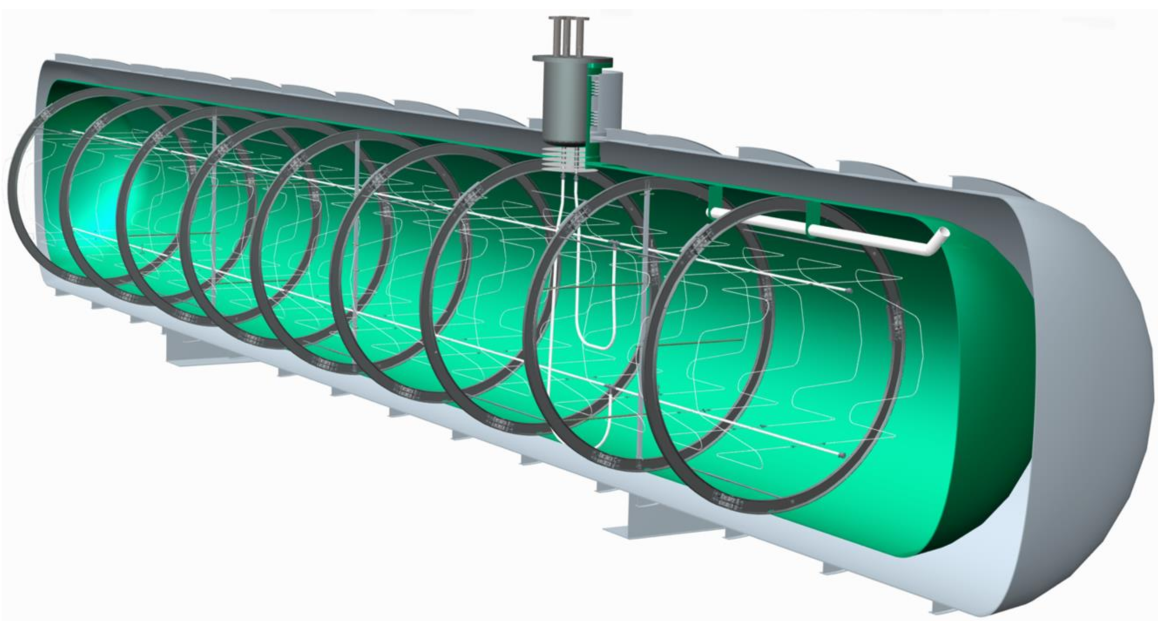

Figure 2. Cut-away view of the 125,000-liter IRAS tank built for GODU-LH2 Project showing internal stiffening rings and IRAS heat exchanger configuration.

While ZBO is the indefinite keeping of cryogenic liquids by matching the tank heat leak, IRAS goes further to provide full control of the state of the fluid: gas, liquid, or densified liquid. Cryogenic systems design approaches are generally built around the passive systems (without active refrigeration) from making the term “non-storable” synonymous with cryogenic propellants. New design approaches, taking advantage of the technology of IRAS, allow for full control of the fluid which gives benefits including simplified liquid densification and keeping; operational reliability and safety; and logistical flexibility. The technology of storable cryofuels makes possible new levels of efficiency as well as new approaches to the supply of hydrogen for transportation applications.

References:

[1] Partridge, J. K., “Fractional consumption of liquid hydrogen and liquid oxygen during the space shuttle program,” Advances in Cryogenic Engineering, AIP Conference, Vol.1434, pp.1765-1770 (2012).

[2] Notardonato, W. U., Johnson, W. L., Swanger, A. M., and Tomsik, T., “Ground Operations Demonstration Unit for Liquid Hydrogen Initial Test Results,” Advances in Cryogenic Engineering, IOP Conf. Series: Materials Science and Engineering 101 (2015).

[3] Swanger, A. M., Notardonato, W. U., Johnson, W. L., and Tomsik, T. M., “Integrated Refrigeration and Storage for Advanced Liquid Hydrogen Operations,” Cryocooler 19: Proceedings of 2016 International Cryocooler Conference, San Diego, California, 513-522 (2016).

[4] Fesmire J E, Tomsik T M, Bonner T, Oliveira J M, Conyers H J, Johnson W L and Notardonato W U, “Integrated heat exchanger design for a cryogenic storage tank,” Advances in Cryogenic Engineering, AIP Conference Proceedings, 1573, 1365-1372 (2014).

[5] Swanger, A. M., Jumper, K. M., Fesmire, J. E., and Notardonato, W. U., “Modification of a Liquid Hydrogen Tank for Integrated Refrigeration and Storage,” Advances in Cryogenic Engineering, IOP Conf. Series: Materials Science and Engineering 101 (2015).

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2017 CEC Papers/Presentations related to IRAS and GODU-LH2

Session C1OrD (Oral Presentation)
Notardonato, et. al., “Zero Boil-Off Control Methods for Large Scale Liquid Hydrogen Tanks using Integrated Refrigeration and Storage”
Poster

Session C1PoJ (Poster)
Notardonato, et. al., “Final Test Results for the Ground Operations Demonstration Unit for Liquid Hydrogen”

Session C1OrD (Oral Presentation)
Swanger, et. al., “Large Scale Production of Densified Hydrogen to the Triple Point and Below”

Additional/Alternate GODU-LH2 Selected Pictures

Storm Clouds Over GODU-LH2 Test Site (NASA Kennedy Space Center)

GODU-LH2 Test Site

Inside the 125,000 Liter IRAS Tank Built for GODU-LH2 Project
Showing Internal Stiffening Rings and IRAS Heat Exchanger